The X-ray calibration facility for the characterization of Gas Pixel Detectors

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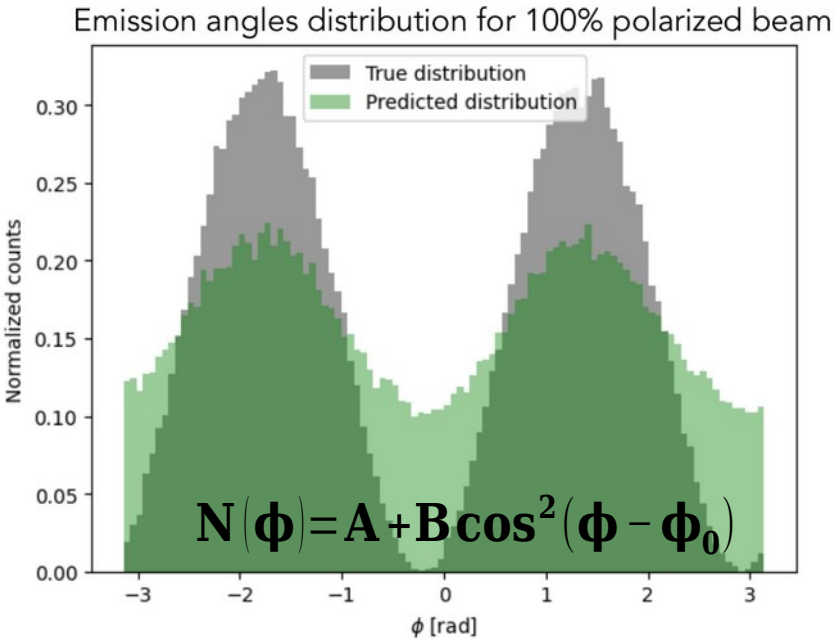
ICFDT7 - 7th International Conference on Frontier in Diagnostic Technologies

Gas Pixel Detector (GPD) for X-ray polarimetry

- Photoelectric effect dominant for soft X-rays (<10keV)
- Photoelectric differential cross section

$$\frac{d\sigma_{ph}^{K}}{d\Omega} = r_0^2 \alpha^4 Z^5 \left(\frac{m_e c^2}{E}\right)^{\frac{7}{2}} \frac{4\sqrt{2}\sin^2\theta\cos^2\phi}{(1+\beta\cos\theta)^4}$$

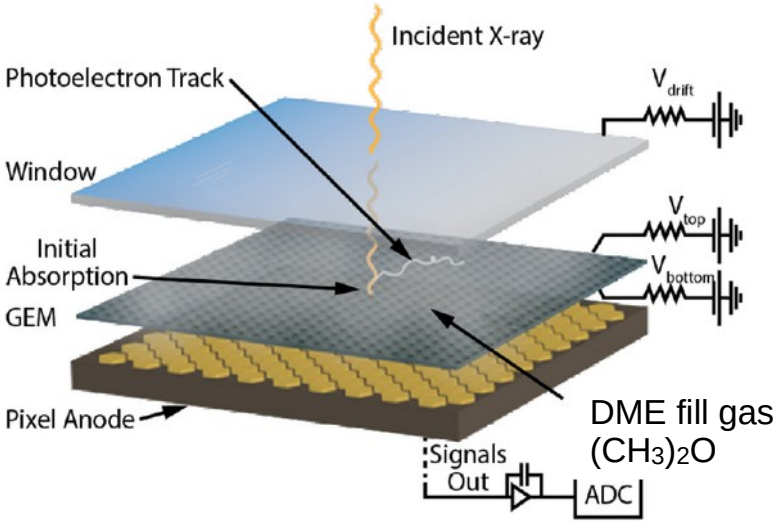
- K-shell photo-electrons **100% modulated** for linearly polarized radiation
- We want to measure the emission direction of the photo-electron

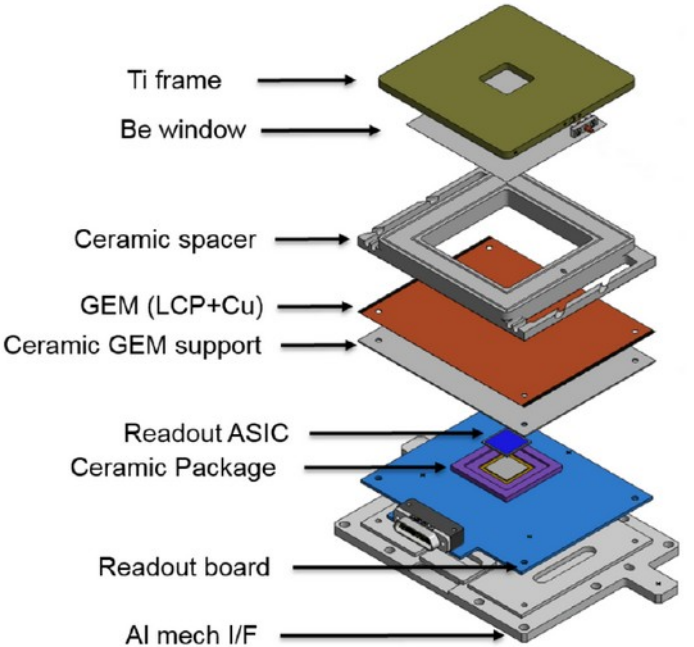


Modulation factor:
reconstructed polarization fraction for a 100% polarized beam

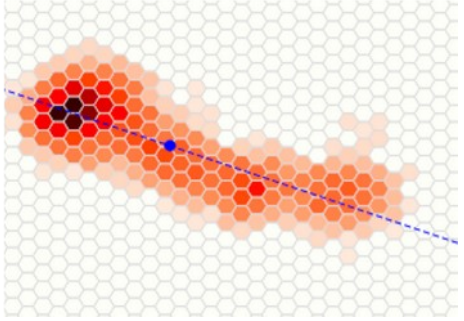
$$\mu = \frac{N_{max} - N_{min}}{N_{max} + N_{min}}$$

GPD overview

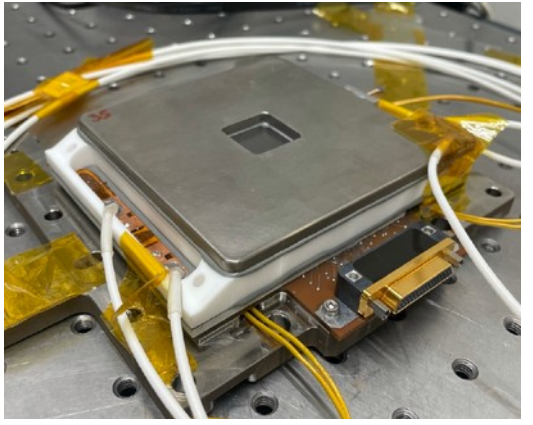




- X-ray absorption in gas
- Signal amplification via GEM (Gas Electron Multiplier)
- Finely pixelized ASIC for readout

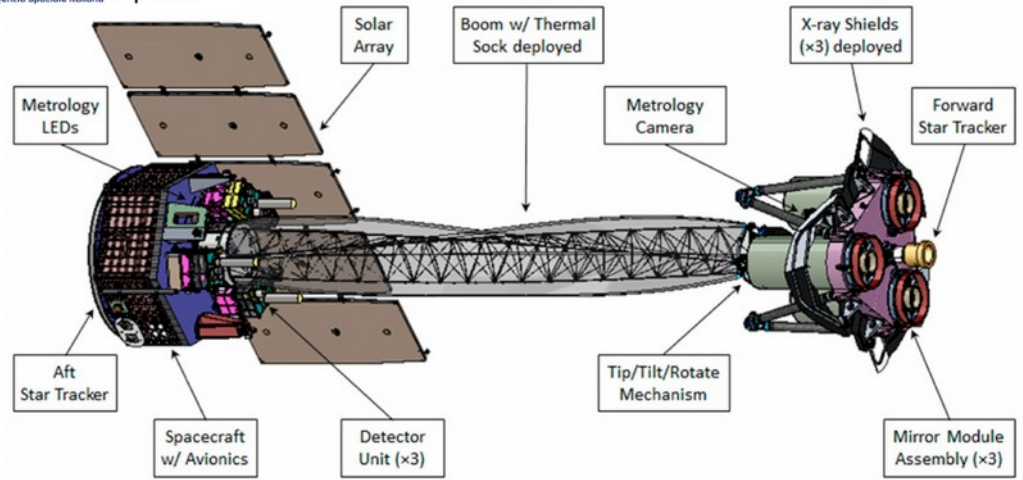


https://doi.org/10.1016/j.astropartphys.2021.102628



IXPE mission

IXPE
Imaging
X-Ray
Polarimetry
Explorer



Study of the linear polarization of astrophysical X-ray sources in the 2-8 keV energy range

- Launch: 9 December 2021.
- Orbit: 600 km, equatorial (inclination 0°).
- Detector: 3 Detector Units (DU), each of them equipped with a Gas Pixel Detector

POLARIZATION: information about the geometry of the emitting matter and of magnetic and gravitational fields

~130 sources observed, ~half of them with measurable x-ray polarization

Check-out a brief history of the field at Weisskopf, Galaxies 2018, 6, 33

XCF: X-ray Calibration Facility

Irradiation setup in Torino aimed to:

- Monitor the long term performances of GPDs
- Test and characterize detectors:
  - new generations of GPDs
  - Position- energy- and polarization-sensitive X-ray detectors.

Main characteristics:

- Two output beams, one polarized by Bragg diffraction at 45°
- Set of 6 polarizing crystals
- Three different x-rays sources
- Positioning stages for detector under test
- Crystal positioning:
  - height
  - θ, φ axes
- Two ancillary detectors (sdd, cmos camera)

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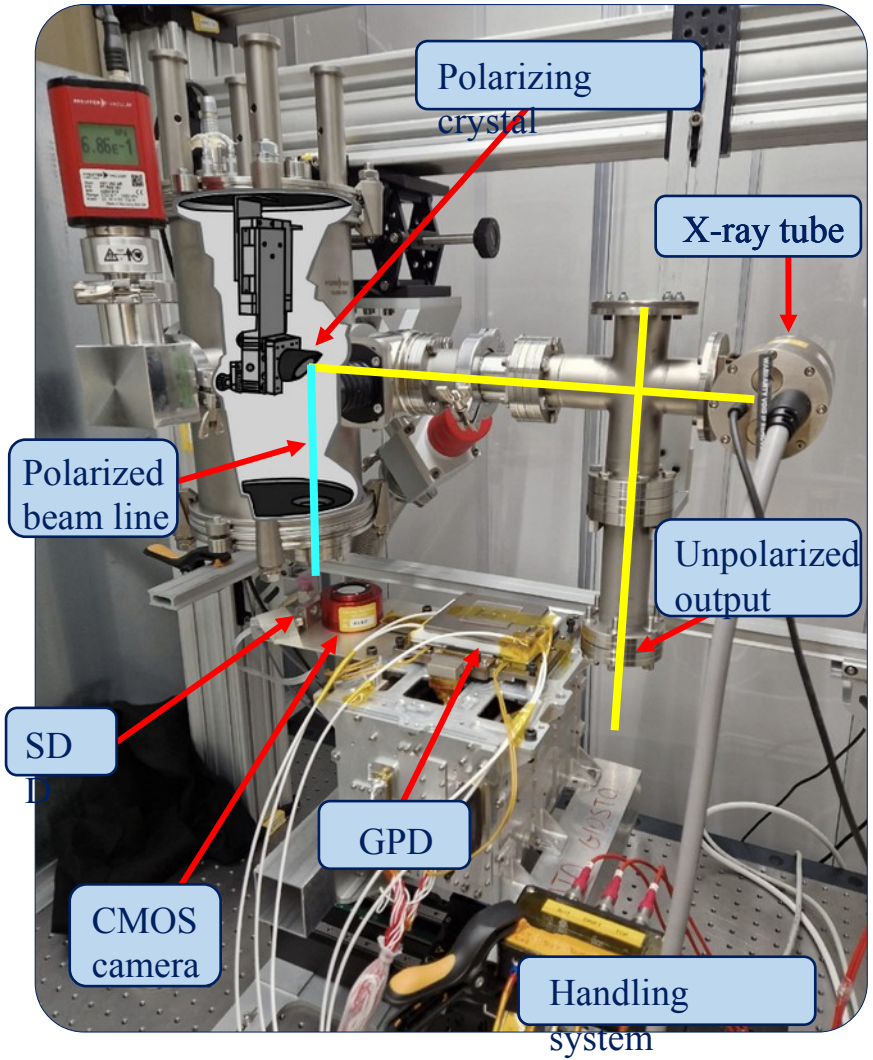


XCF: X-ray sources

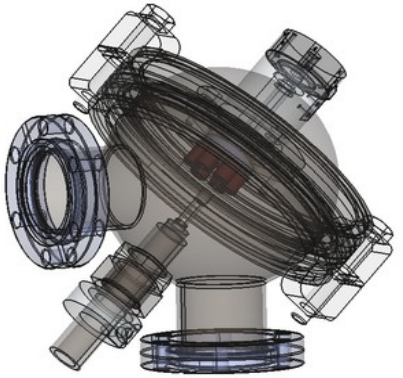
- **McPherson mod 462**

  6 interchangeable solid anodes, dual beam output

  Power: 30W, 10 kV max, 3mA

Anode	Mo	Rh	Pd	Ti	Fe	Ni
Line	Lα	Lα	Lα	Kα	Kα	Kα
E [KeV]	2.293	2.697	2.839	4.511	6.404	7.478

  (currently showing some stability problems… **)**



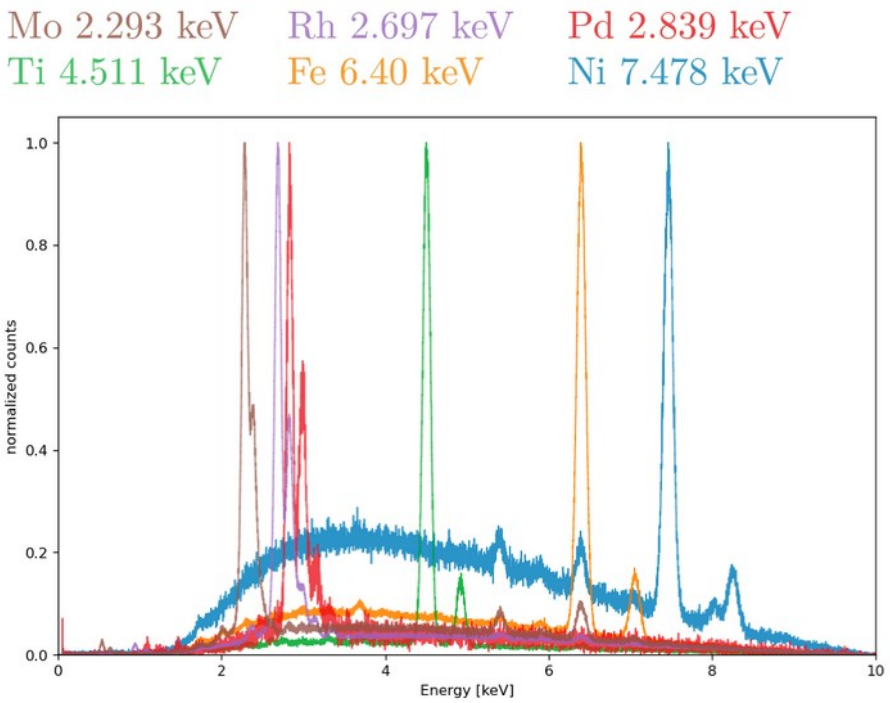
- **MXR selead tube**:

  Mo anode (Lα= 2.294 keV)

- **^{55}Fe source**

  1mCu

  Kα = 5.9keV, Kβ=6.5keV



Ancillary detectors

- Amptec fast SDD

25 mm² active area

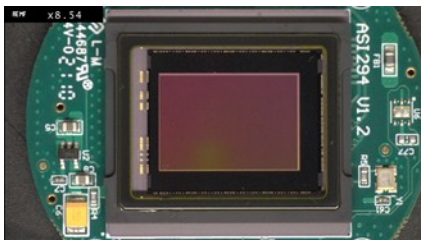
Resolution of 122 eV FWHM at 5.9 keV ~2%

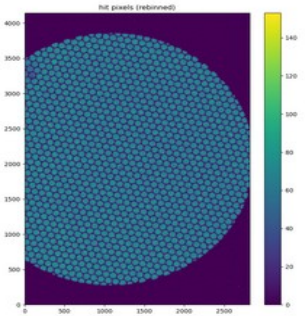
Count rates > 1,000,000 CPS

Windows: Be 12.5 µm

- Modified* optical sensor (sony IMX294)

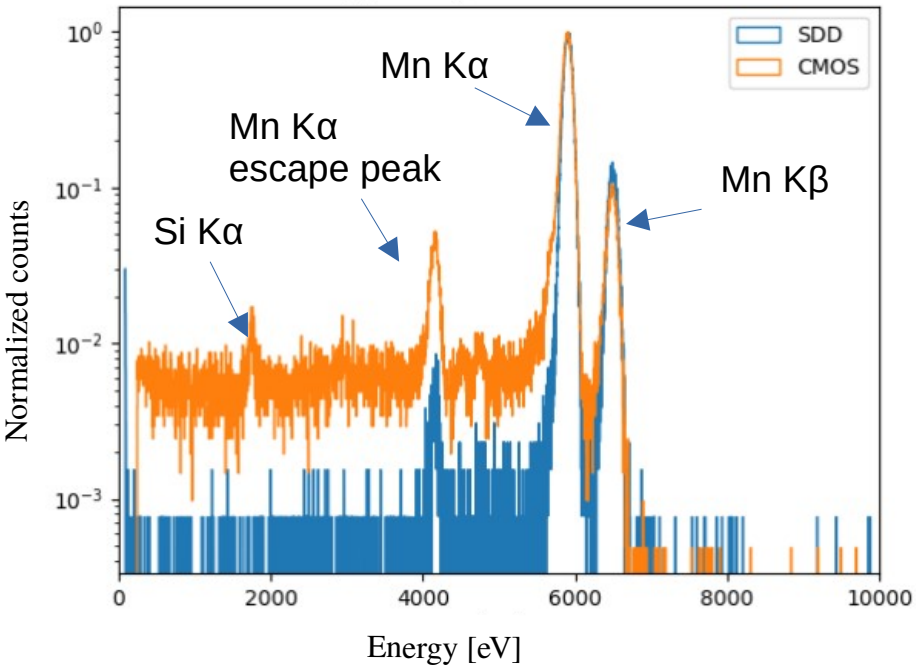
*glass cover removed



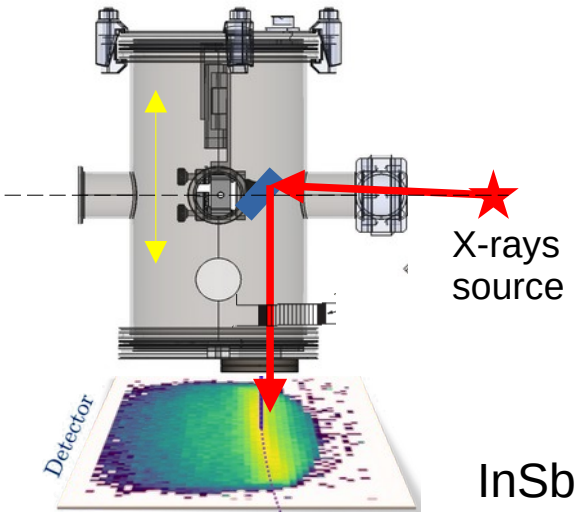


4144x2822 pixels (4.63 um)
14 bit ADC
Energy resolution (FWHM) ~2.2% @6keV
Efficiency ~10% @6keV w.r.t SDD

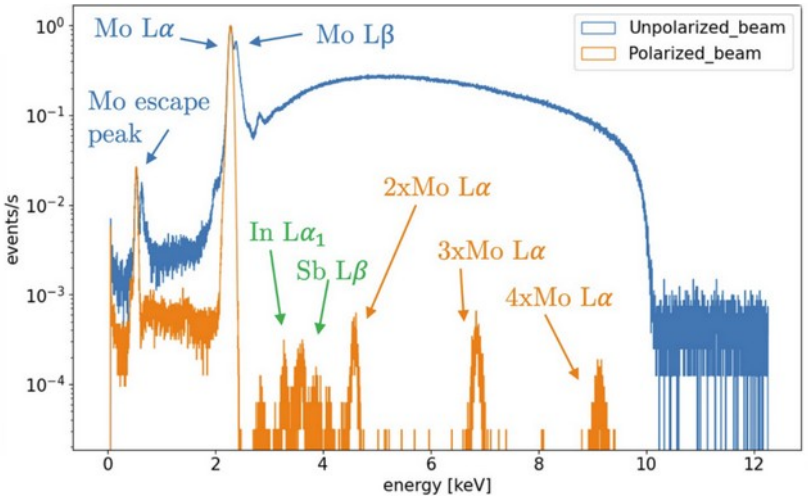
^{55}Fe energy spectrum



Polarized beam



InSb111



Polarization by Bragg diffraction at 45°

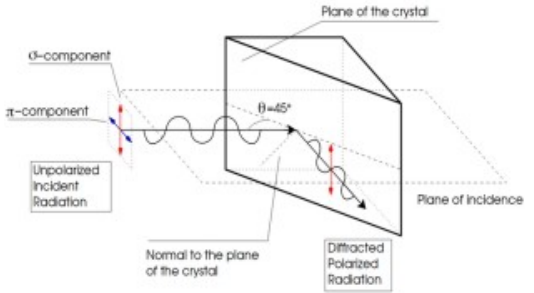
$$\sin(\theta_{Bragg}) = \frac{nhc}{2dE}$$

Polarization degree:

$$\mathcal{P} = \frac{1-k}{1+k}$$

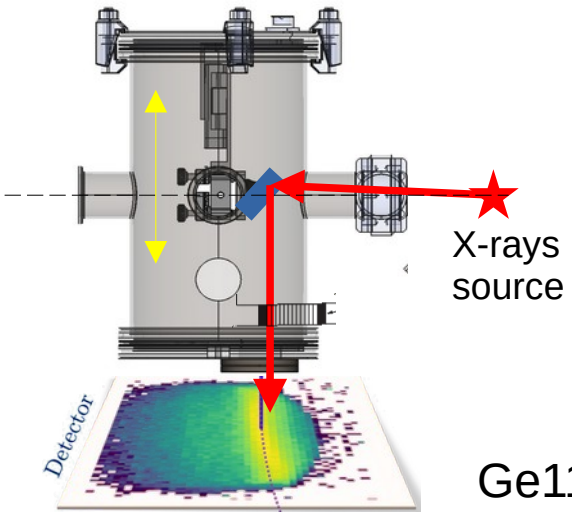
With:

$$k = \frac{R^{\pi}}{R^{\sigma}} \approx 0 \quad \text{for} \quad \theta_{Bragg} \approx 0$$

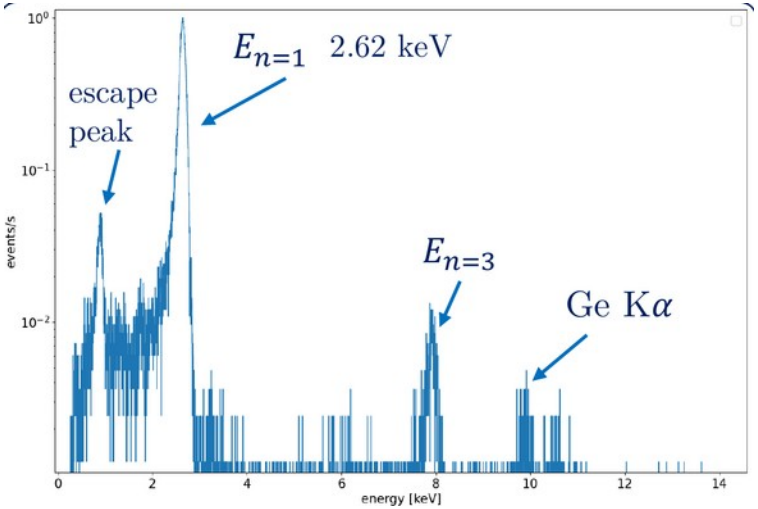


Crystal	Energia [keV]	θ Bragg	P [%]
InSb 111	2.28	46.6 °	~99
Ge 111	2.62	46.5 °	~99
Si 111	2.82	44.4 °	~99
Si 220	4.45	46.6 °	~98
Si 400	6.32	46.3 °	~99
Ge 422	7.43	46.2 °	~99

Polarized beam



Ge111



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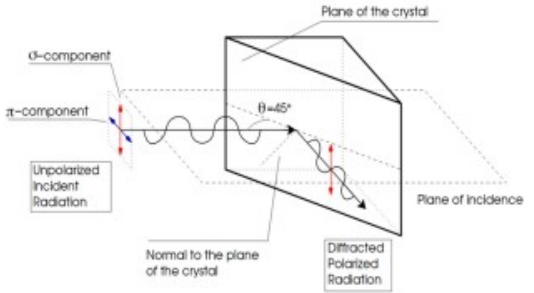

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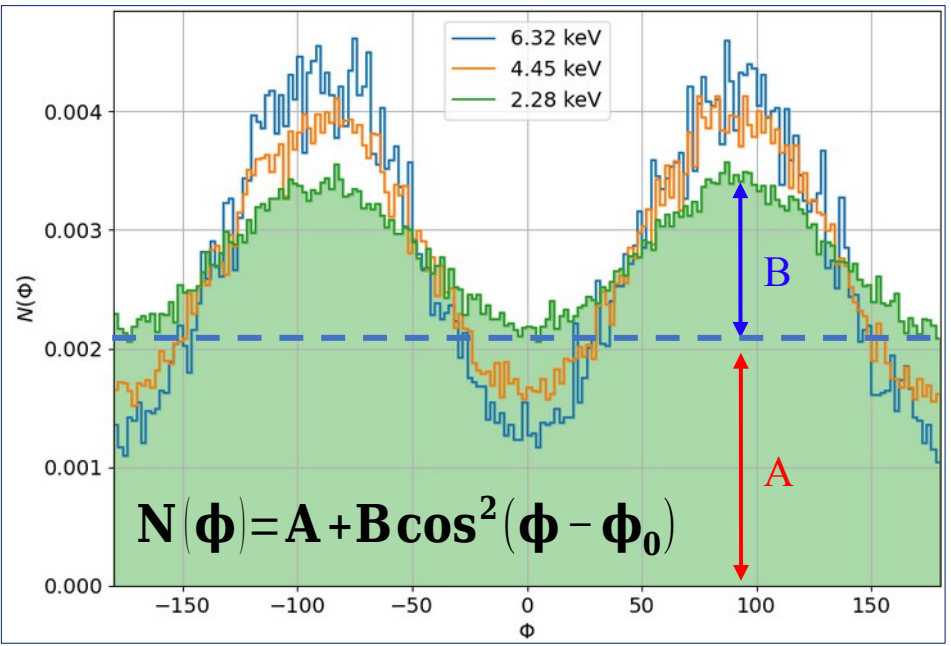
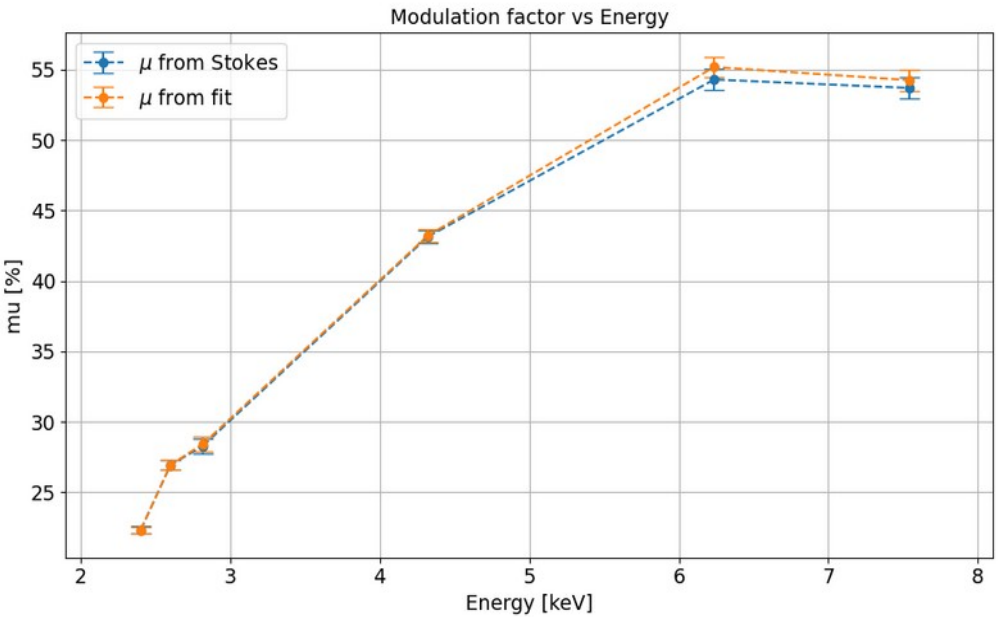
GPD test and characterization @XCF

modulation factor (E)





Conclusions

- Gas Pixel Detectors opened a new “window” on the polarization of x-rays astrophysical sources

- The X-Ray calibration facility @ Torino is an x-rays irradiation setup in the energy range 2-8 keV.

  - Can provide polarized (almost monochromatic) and not polarized beams

  - Main goals:
    - study the long term evolution of IXPE GPDs
    - test and calibration of new GPD prototypes
    - test and characterize generic position- energy- and polarization-sensitive X-ray detectors.

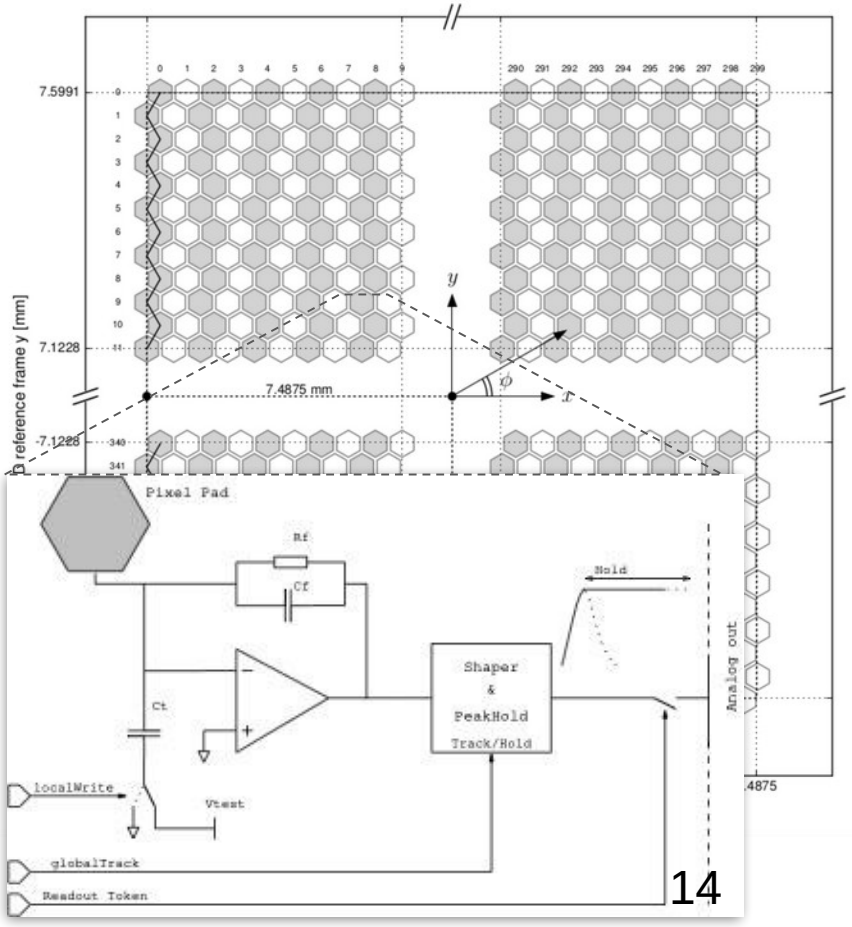
The IXPE XPOL chip layout and single pixel FE chain

CMOS VLSI chip built with 180nm technology

- 16M+ transistors
- 105k hexagonal pixels (300x352)
- 15mm^2 - 470 pixel/mm^2 density

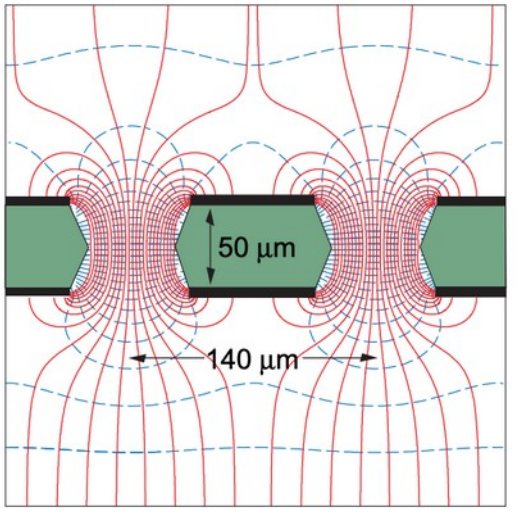
Each pixel contains

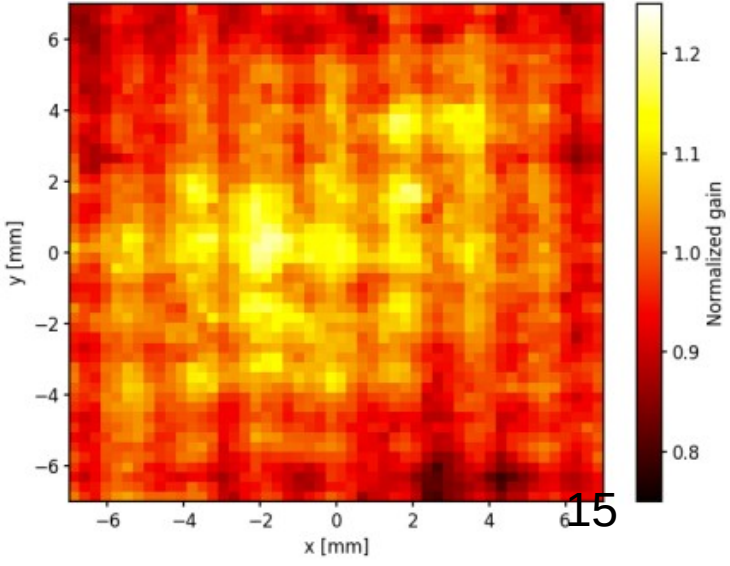
- Hexagonal metal top layer
- Charge sensitive amplifier (~400mV/fC)
- Shaping circuit (~4usec)
- Low noise (<30e ENC)
- Multiplexer to external ADC (1V dynamic, ~30ke)



The IXPE GEM

Parameter	Value
Number of holes	112008 (359 × 312)
Horizontal pitch	43.30 μm
Vertical pitch	50.00 μm
Hole diameter	30 μm
Hole diameter dispersion	~ 1 μm (typical)
Top-bottom alignment	~ 2 μm (typical)
Metal coating	Copper
Coating thickness	5 μm
Substrate	Liquid crystal polymer (LCP)
Substrate thickness	50 μm
Manufacturing process	Laser etching
Typical operating voltage	~ 470 V
Gain gain scaling	$\propto$ exp(~ 0.03 V)
Working effective gain	~ 200

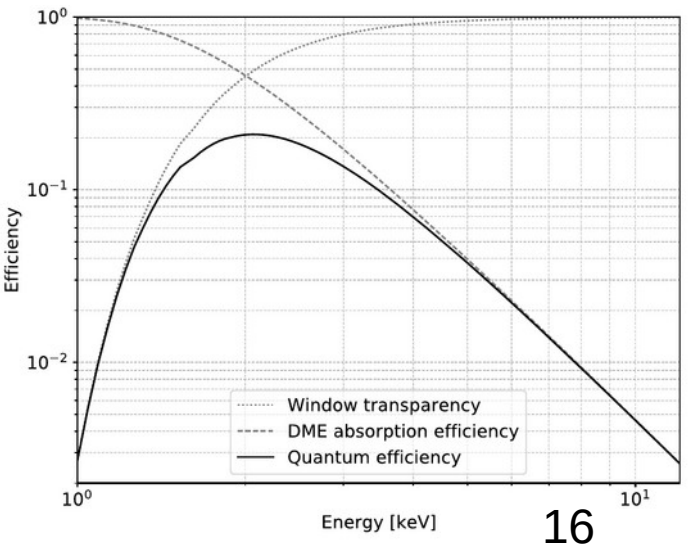


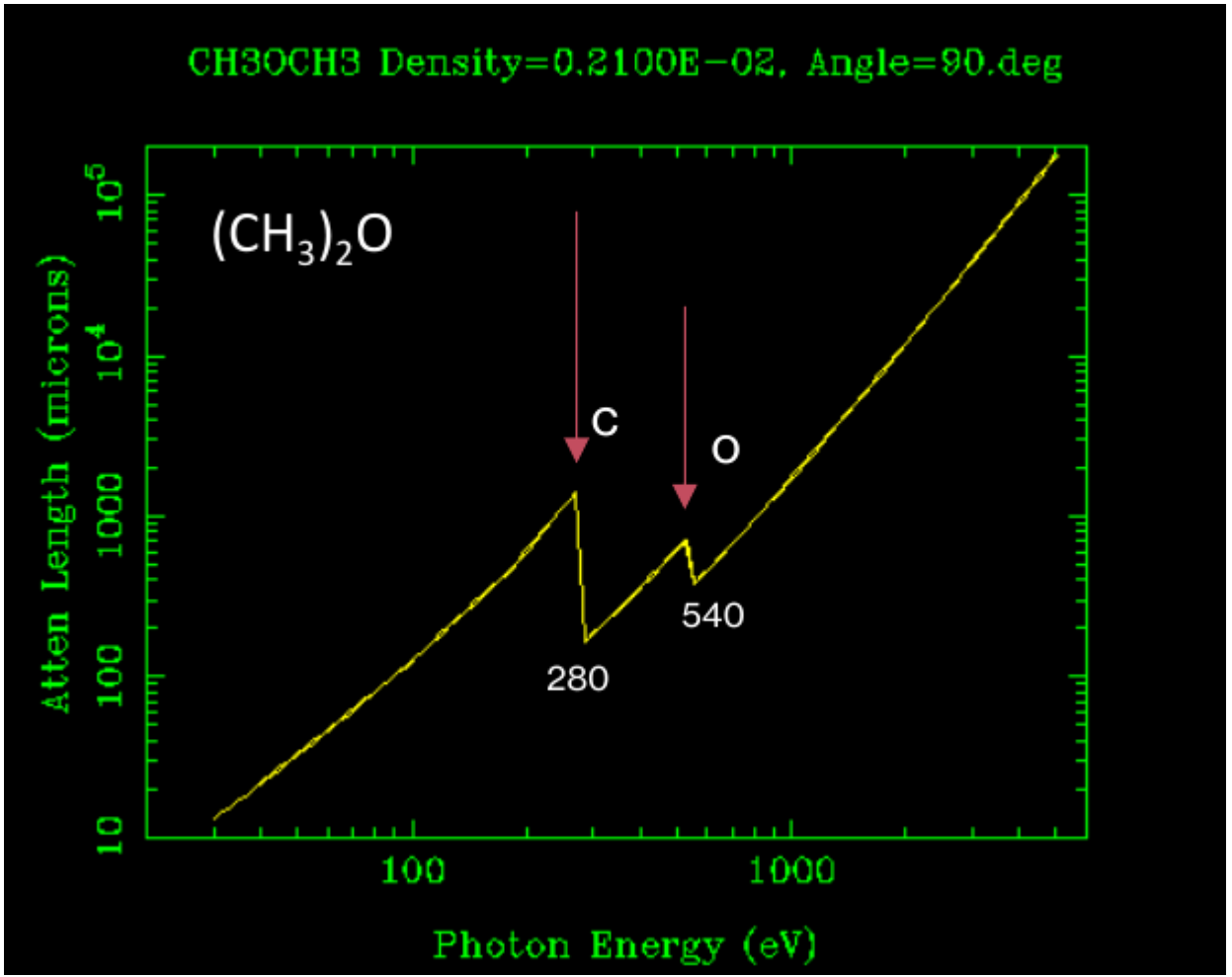


GPD performances

Parameter	Typical value
Effective noise	22.5 electrons ENC
Gain uniformity	~20%
Energy resolution	~17.5% FWHM at 5.9 keV
Position resolution	<100 μm rms
Modulation factor	~28% – 55% @ 2.7–6.4 keV
Spurious modulation	< 0.5% at 5.9 keV
Trigger efficiency	~100% down to 1 keV
Dead time per event	~1 ms at 2.7 keV

Quantum efficiency




CH3OCH3 Density=0.2100E-02, Angle=90.deg
$(CH_3)_2O$
C
O
280
540
Atten Length (microns)
10
100
1000
10^4
10^5
100
1000
Photon Energy (eV)

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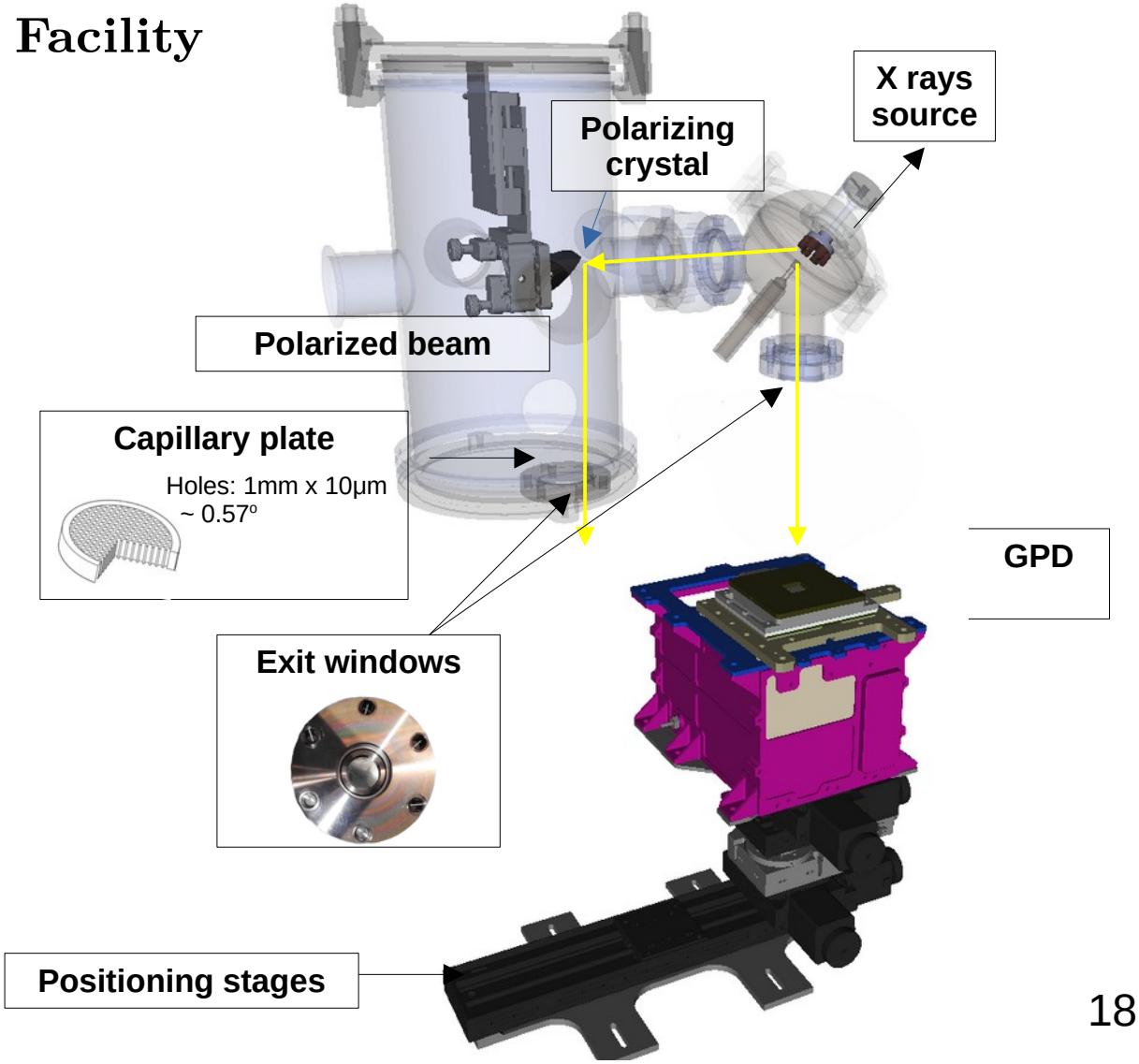
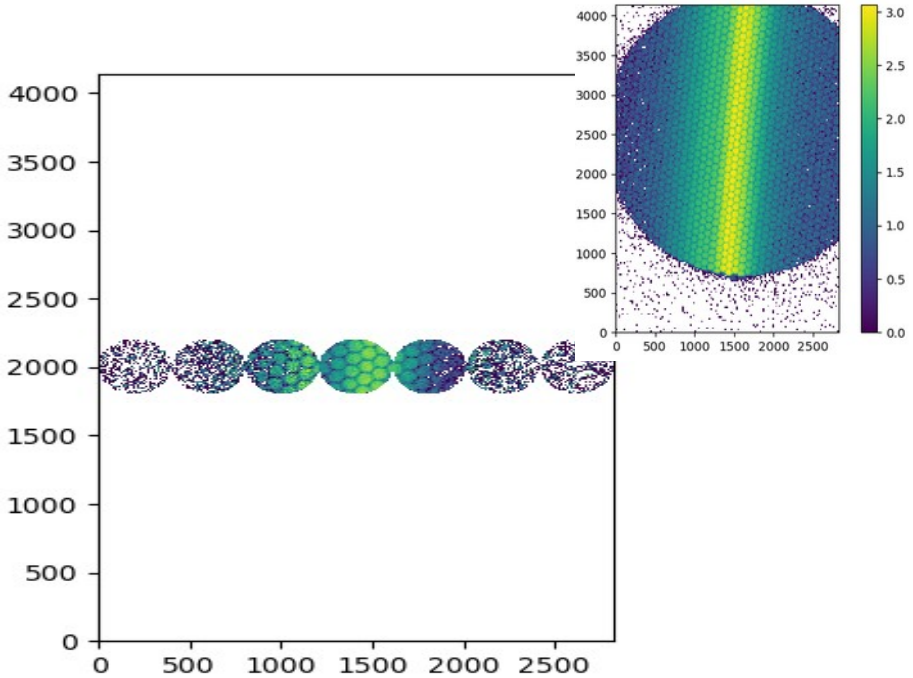
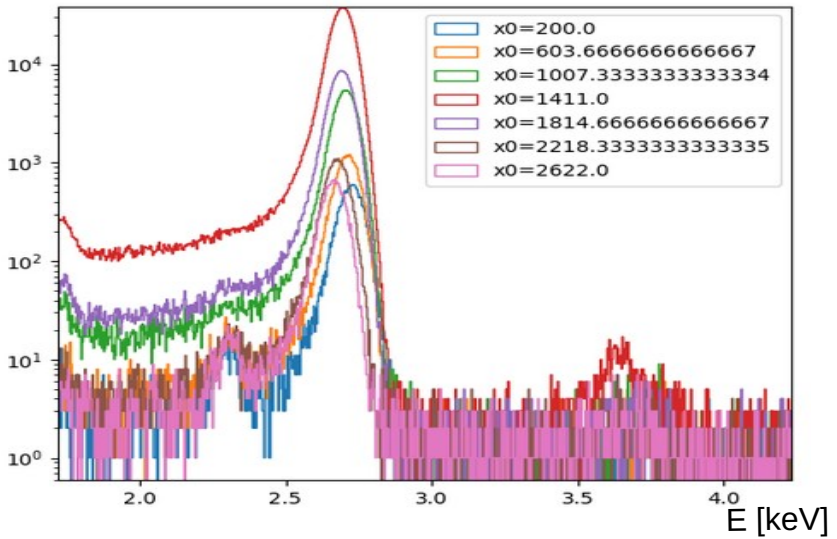


Rh-Ge111: energy-position





As expected different energies are diffracted at different angles

Peak energy vs position